

AN OVERVIEW OF THE DEFENCE RESEARCH AGENCY PHOTOVOLTAIC PROGRAMME

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INTRODUCTION

The DRA has been active in the photovoltaic field since the early 1960's, then as the Royal Aircraft Establishment (RAE). The early work was aimed at developing silicon cells, solar panels and light-weight flexible arrays in support of the "UK" and "X" series of British scientific and technology satellites (ref. 1), for which the RAE was either the design authority or technical advisor. The X3 satellite - Prospero, (fig. 1), launched in 1971 test flew 50 micron wrap-round silicon cells (ref. 2). The X4 satellite - Miranda, launched in 1974 test flew a deployable flexible silicon array which was developed at the DRA (ref. 3). During this period an extensive range of test equipment was developed which has been maintained, modernised and extended to date.

Following a period of reduced activity in the late 1970's and early 1980's the current programme has evolved. This paper briefly summarises the programmes that have been undertaken since 1983. These range from various cell developments, new types of coverglasses, flight experiments, radiation testing, primary cell calibration and environmental testing.

The current photovoltaic programme is mainly funded by the UK Ministry of Defence and by the Department of Trade and Industry through the British National Space Centre (BNSC). The programme is aimed at research and development, both internally and with Industry, to meet the customer's technical objectives and requirements and to provide them with technical advice. The facilities are also being used on contract work for various national and international organisations.

CELL DEVELOPMENT

SILICON

Due to the lack of a UK manufacturer very little has been carried out on silicon cells. The only work carried out was a study into the effects of incorporating an oxygen denuded zone and a defect gettering zone into a silicon cell to improve the radiation resistance (ref. 4). DLTS studies had shown that the main recombination defects involved oxygen and by removing this oxygen it was hoped that the radiation resistance would be improved. The initial results showed that the cells were very radiation hard but suffered from a poor performance. The cell efficiency only matched that of a conventional cell at a fluence of $1 \times 10^{15} \text{ e/cm}^2$ 1 MeV electrons. This technology is currently being looked at again to see if by varying the depth of the denuded zone the performance can be improved and still retain the radiation resistance.

GALLIUM ARSENIDE

The main cell development has been the development of GaAs cells at EEV. The first phase was the development of infinite melt liquid phase epitaxy (IMLPE) cells, (fig. 2), which has resulted in the commissioning of a 1 kW pilot production line with batch averages of over 18% and a best production cell of 19.6%, as measured at DRA (refs. 5,6). A 15 W power panel of these cells is being flight tested on the UoSAT-5 satellite and is performing

as expected. A production run in excess of twelve hundred 22 x 20 mm cells has been made to demonstrate the production line and to provide cells for three panels on the STRV-1A satellite (ref. 7).

The second phase is the development of MOCVD GaAs and GaAs/Ge cells. This is a joint DRA-European Space Agency (ESA) programme which consists of the installation and commissioning of a Quantax MOCVD reactor, the development of a mathematical model for GaAs/Ge cells, and the production of both 2 x 2 cm MOCVD GaAs and GaAs/Ge cells. The programme has recently been extended to include the development of 40 x 40 mm GaAs/Ge cells and is currently scheduled to be completed in March 1993. To date GaAs cells of over 19% efficiency have been produced through this programme.

The third phase is the development of ultra-thin GaAs cells. This involves the etching away of the substrate to leave a 10-20 micron thick solar cell supported by the coverglass. Initial trials using an adhesive bonded coverglass resulted in a best cell of 19.7%. Current activities concern the use of directly glassed coverglasses on a GaAs/Ge cell grown with an etch stop layer to produce ultra-thin devices. Work is also being undertaken into various interconnection methods as there are problems associated with the ultra-thin cells cracking at the contact pads.

INDIUM PHOSPHIDE

A development programme into ITO/InP cells was undertaken at Newcastle Polytechnic (ref. 8) which produced small area devices over 16% efficient and 2 x 2 cm devices over 13% efficient. It also resulted in the first flight of ITO/InP cells in space on the LIPS III satellite, which is discussed later. In addition to developing the cells, radiation studies were performed to assess their resistance compared to GaAs and Si cells (refs. 9-11). On completion of this programme a consortium of UK Industry and academia have continued the development of the ITO/InP cells along with new work aimed at developing homojunction InP and InP/Si cells under the UK Department of Trade and Industry LINK advanced semiconductor materials programme (refs. 12,13).

COVERGLASS DEVELOPMENT

DRA's involvement in solar cell coverglasses technology has over the years resulted in the development of various types of coverglass and coatings at Pilkington Space Technology.

The first coverglass to be developed was the CMS coverglass in the early 1970's, a borosilicate glass stabilised with cerium oxide against darkening induced by electron, proton and UV irradiation. This was followed in the early 1980's by a new composition designated CMX with improved transmission properties over the CMS glass (ref. 14).

With the introduction of larger area silicon cells and new coverglass bonding techniques the difference in thermal coefficient of expansion between CMX and Si can cause interface stresses. This led to the development of the CMZ coverglass which has the same optical properties and radiation stability as the CMX glass but with the thermal coefficient of expansion matched to that of silicon from -200°C to 500°C (refs. 15,16).

After completion of the CMZ development a programme was started into the direct glassing of silicon cells using electrostatic bonding (refs. 17,18). Several problems were incurred due to the anti-reflection coating on the cells, silver migration from the fingers into the coverglass and the grid finger height. This resulted in collaboration with ESA and Telefunken System Technik (TST). On completion of the first phase under the UK national programme, the second phase became a joint UK-German programme run through ESTEC with DRA providing support. A viable bonding process has been produced from this programme (refs. 19,20).

With the introduction of GaAs cells a new glass was developed to be thermally matched to GaAs. The resulting glass designated CMG has superior optical and thermo-optical properties to CMX and same radiation stability but has a thermal coefficient of expansion matched to GaAs from -180°C to 520°C (refs. 21,22).

Following the successful development of the CMG glass and the results of the silicon direct glassing programme a new DRA programme has commenced on the direct glassing of GaAs cells at Pilkington Space Technology and EEV.

In addition to the coverglass development two optical coatings have been developed to improve the thermo-optical properties of the glasses, an ultra-violet reflection (UVR) coating and a high emissivity (HE) coating. The ceria doped coverglasses absorb UV preventing coverglass adhesive darkening but in the process generate heat. The purpose of the UVR coating is to reflect the UV and so reducing the solar absorptance and hence lowering the temperature of the solar cell assembly. The HE coating increases the absorptance in the 8-12 micron region where the reststrahlen reflection bands from the silicon oxide in the glass occur. These bands lower the emittance of the glass, by suppressing them it is possible to increase the emittance (ref. 23).

All the glass types and coatings described above were subjected to an environmental test programme at DRA to demonstrate their suitability in the space environment.

FLIGHT EXPERIMENTS

LIPS-III

The DRA flight testing programme began with the flight of a small panel on the Naval Research Laboratory LIPS-III satellite (ref. 24), launched in Spring 1987. The panel was made up of four strings of silicon cells each with a different type of coverglass: standard CMX, CMX with an ultra-violet rejection coating, CMX with a high emissivity coating and CMZ. In addition to this were a string of radiation hard denuded zone silicon cells and four 2 x 2 cm ITO/InP cells. Unfortunately I-V and temperature measurement problems have been experienced which have limited the usefulness of the results from the experiment. After four years in orbit it is believed that the ITO/InP and denuded zone silicon cells have possibly degraded by 1% in Isc and all the coverglass strings by approximately 6% in Isc (see fig. 3), which is in broad agreement with the predicted degradation (refs. 11,12).

UoSAT-4

LIPS-III was followed by the UoSAT-4 solar cell experiment. UoSAT-4 was a 50 kg microsatellite designed and built by the University of Surrey. The satellite was powered by two panels of Mitsubishi LPE GaAs, a panel of CISE LPE GaAs and a half panel of LPE GaAs from the DRA development contact at EEV. DRA was responsible for the design, manufacture and acceptance testing of the Mitsubishi and EEV panels. DRA also undertook the design, manufacture and testing of the solar cell experiment (Surrey University provided the measurement electronics). The time period from the start of the design to delivery of the experiment was 9 months.

The purpose of the experiment was to test fly the cell and coverglass components currently under development and to compare them with devices from other international organisations. The experiment comprised of six strings of silicon cells, different types of coverglasses and coverglass bonding techniques, GaAs from EEV, CISE and ASEC, and InP from Newcastle Polytechnic and the Nippon Mining Company.

UoSAT-4 was successfully launched into an 800 km polar orbit on 22 January 1990 by an Ariane-4 launcher. Unfortunately 25 hours after activation all telemetry was lost from the satellite and has never been recovered.

UoSAT-5

Following the loss of UoSAT-4 the opportunity arose to fly an experiment on UoSAT-5 as a replacement (fig. 4). The experiment was redesigned to fly individual cells instead of strings and the electronics redesigned to be similar to the STRV electronics. The experiment is comprised of silicon cells with different types of coverglasses and coverglass bonding techniques, IMLPE GaAs, MOCVD GaAs, GaAs/Ge, Cleft GaAs, ITO/InP and homojunction InP (fig. 5). The cells and coverglasses were supplied by UK Industry and in collaboration with NASA Lewis and Wright Laboratory.

UoSAT-5 was successfully launched into a 770 km sun-synchronous orbit on 17 July 1991 by an Ariane-4 launcher as a secondary payload to ERS-1. Unfortunately I-V and temperature measurement problems have again been experienced on the experiment, although not as serious as on LIPS-III. Good Isc data is being received, reasonable Pmax data but the Voc is subject to an offset due to a measurement problem and the temperature resolution is too coarse. None of these problems are serious and good in-orbit performance data is being produced. After 1 year in orbit degradation is being seen on the cells roughly in line with that expected with one major anomaly: all three ITO/InP cells, from two different manufacturers are showing far more degradation than was expected, ground results have implied that little or no degradation should be seen. This result is currently under investigation. Data is continuing to be received from the experiment.

EURECA

The next experiment was the Advanced Solar GaAs Array (ASGA) experiment on the European Space Agency EURECA retrievable platform which was launched in the summer 1992 by the Space Shuttle on a 6 month flight and will then be recovered. The ASGA experiment is a collaboration between DRA and ASI (the Italian Space Agency) to fly a panel containing three cassegrainian concentrator modules (refs. 25,26). Pilkington Space Technology under contract to DRA manufactured the concentrator modules and integrated them onto the panel, see Figure 6. The completed panel was then electrically tested at DRA before shipping to ASI for integration on to EURECA. Post flight analysis will be undertaken to determine the effect of the LEO environment on the materials used and electrical tests on the modules to assess any degradation.

STRV-1

These flight experiments will be followed by a solar cell experiment on STRV-1B which should be launched into Geostationary Transfer Orbit (GTO) at the end of 1993. STRV-1B is a 50 kg microsatellite being developed at the DRA, see Figure 7 (ref. 27). Its purpose is to act as a test vehicle for new satellite technologies. Due to the GTO orbit, see Figure 8, the radiation environment is very severe. This allows for lifetime radiation testing of solar cell technologies to be performed in a short time scale. The nominal mission life is one year. The solar cell experiment will have the capability to measure the I-V curve and temperature of a maximum of 47 cells.

The list of cells to fly is still being drawn up but is likely to be made up of a wide range of technologies, Si, GaAs and its derivatives, InP, CIS, etc. supplied via Phillips Laboratory, NASA Lewis or DRA.

In addition to this the current at 28 V will be monitored on solar panels of STRV-1B and it's sister satellite STRV-1A which will be launched at the same time. These panels will be EEV IMLPE GaAs, EEV MOCVD GaAs or GaAs/Ge, CISE/FIAR IMLPE GaAs supplied via ESTEC, Spectrolab GaAs/Ge and ASEC GaAs/Ge supplied via Phillips Laboratory.

ENVIRONMENTAL TESTING

RADIATION EFFECTS

Radiation studies have been performed since the late 1960's (refs. 28,29,30). More recent work has concentrated on an internal programme of isotropic proton irradiation of silicon, GaAs and InP cells (refs. 9,10,11) and defect studies using Deep Level Transient Spectroscopy (DLTS) on silicon and GaAs cells at Southampton University.

We have access to several facilities at AEA Technology, Harwell, to perform electron and proton irradiations. We use a 0.6-1.2 MeV Van De Graaff accelerator for electrons, a 0.5-1.8 MeV Van De Graaff accelerator and a 2-10 MeV tandem Van De Graaff accelerator for protons. To simulate isotropic irradiation a 'rocker' is used on the end of the proton beam line (ref. 9).

The defect study at Southampton University used DLTS on proton and electron irradiated silicon and GaAs solar cells to identify the nature of the defects causing the electrical degradation (ref. 31). A new technique was

used, recombination DLTS which uses a laser to inject minority carriers into the device. This allows both majority and minority recombination centres to be identified.

The current programme consists of three main activities: an annealing study into the removal of proton damage from silicon and GaAs cells, an investigation into the radiation characteristics of advanced cell types and the production of accurate damage coefficients for cells which will fly on the STRV-1B solar cell experiment to allow a comparison between the predicted and actual degradation to be made.

The annealing study is aimed at determining the minimum temperatures required to remove low energy proton damage from silicon and GaAs and to determine whether it is possible to lower the temperature when large currents are injected, recombination enhanced annealing.

TEST FACILITIES

To support the above activities an extensive test laboratory is maintained at the DRA for electrical and thermal testing.

For I-V measurement two simulators are available: a Spectrolab X25 continuous simulator and a Large Area Pulsed Solar Simulator (LAPSS). The X25 beam is directed onto a temperature controlled block enabling the I-V curve for cells from 2 x 2 cm to 10 x 10 cm to be measured at temperatures ranging from +10°C to +115°C. A similar block is used on the LAPSS allowing 2 x 2 cm cells to be measured but in addition panels can also be tested, a maximum of 50 A and 100 V output.

The LAPSS facility is not suitable for testing a commercial satellite solar array however after it has been integrated on to the satellite. To overcome this a smaller version of the LAPSS was developed at DRA (ref. 32) to measure the performance of the solar panels before and after the satellites go through their environmental testing and to perform a pre-launch check at the launch sites. This was successfully used on the three MOD Skynet-4 and the two NATO-4 communications satellites.

In addition to the I-V measurements the relative spectral response (RSR) of cells can be measured using monochromatic light from a narrow band filtered xenon lamp at 25 nm steps from 300 to 1200 nm with or without AMO white light bias.

Standard solar cells are used to calibrate the simulators. DRA has for many years calibrated solar cells using terrestrial sunlight in either Cyprus or Malta (ref. 33). The DRA calibration method uses total radiation from sky and sun. This technique involves the measurement of the cell's RSR, I_{sc} in sunlight, solar intensity and the relative spectral energy distribution of the sunlight. From these measurements, the solar cell's short circuit current can be calculated for any AM0 or terrestrial spectrum. The advantage of the DRA terrestrial method is that a large number of cells, up to 10 x 10 cm in size, can be calibrated reasonably quickly at a relatively low cost per cell, at least 150 cells during a two week period.

A comparison was carried out in 1980 to compare this method with the JPL and CNES balloon flights and NASA's high altitude aircraft (ref. 34), the outcome was that all the methods agreed to $\pm 1\%$. Current activities are the improvement of the equipment and a repeat of the 1980 comparison, including a comparison of predicted performance using the standards against actual in-flight results on the solar cell experiments.

Besides the electrical measurement equipment, the section has a range of thermal test facilities: a rapid thermal cycling rig, a thermal vacuum chamber and a solar thermal vacuum chamber. These are for testing individual cells and coverglass, coupons and small solar panels, eg. STRV and UoSAT size.

The rapid thermal cycling equipment can cycle small test coupons up to 22 x 11 cm or individual components between a maximum of +150 and a minimum of -170°C in a nitrogen gas atmosphere. The cycle time depends upon the temperatures and the mass of the samples, a typical Al panel will take approximately 10 minutes a cycle between $\pm 100^\circ\text{C}$.

The thermal vacuum chamber is used to outgas and thermal cycle coupons or small solar panels. The maximum panel size is 60 x 40 cm. The maximum temperature is +200°C and the minimum temperature is -130°C.

The Solar Thermal Vacuum chamber can thermally cycle a panel of up to 27 x 26 cm between temperatures of +100 and -200°C in vacuum. The heating part of the cycle is achieved by illuminating the front of the panel through a port with light from an X25 solar simulator, supplementary heating from an internal wire heater is available if required. The rear of the panel faces a liquid nitrogen shroud, ie the front is in 'sunlight' and the rear 'deep space'. The light beam and heaters are shut off to go into 'eclipse'. If a deep eclipse is to be simulated, eg for GEO then the sample is lowered into a separate part of the chamber where it is completely surrounded by a liquid nitrogen shroud and also cooled by a helium refrigeration unit to improve the cooling rate. Using computer control GEO or LEO representative thermal cycling can be achieved. Future work is planned as part of an ESA activity on thermal control.

The above facilities are currently being used to qualify the EEV cells and panels which are to fly on STRV-1A and 1B. Along with other equipment, qualification tests can be performed in accordance with the ESA Generic specification for silicon solar cells PSS-01-604 and the USAF MIL-C-83443B general specification for Space solar cells and assemblies.

CONCLUDING REMARKS

The DRA photovoltaic programme has been wide ranging in its activities: developing new coverglasses, developing GaAs and InP solar cells, performing flight experiments, radiation testing, primary cell calibration and environmental testing. Further activities are planned in these areas to meet requirements of the British military and civil space programmes and other national and international bodies.

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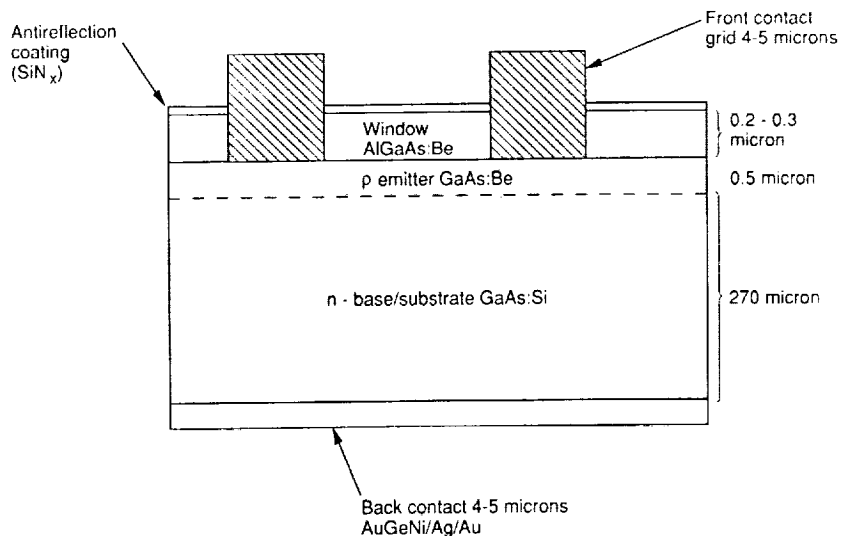
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**Fig 2 The EEV IMPL GaAs
solar cell**

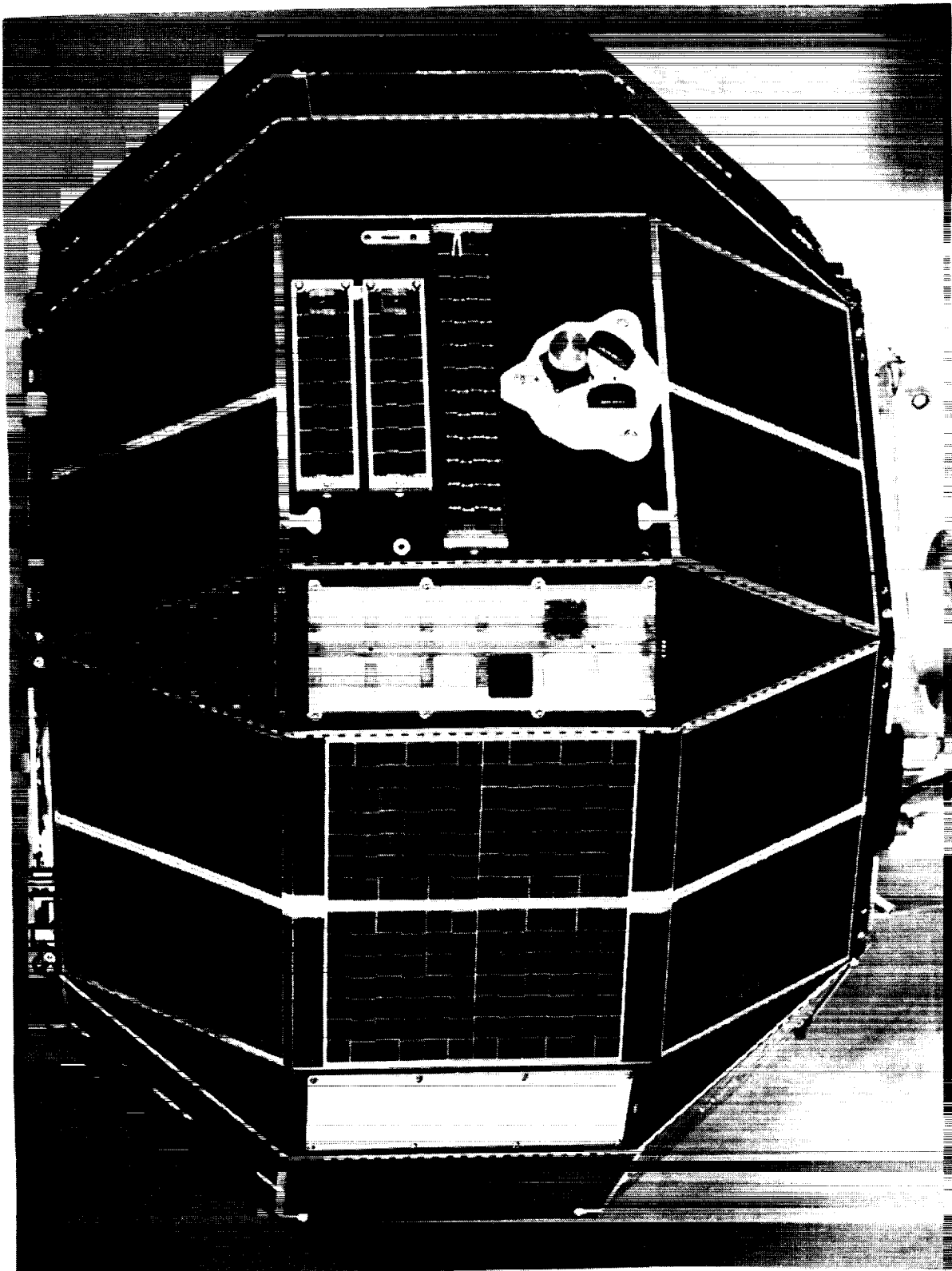


Fig 1 The UK-3 satellite - Prospero

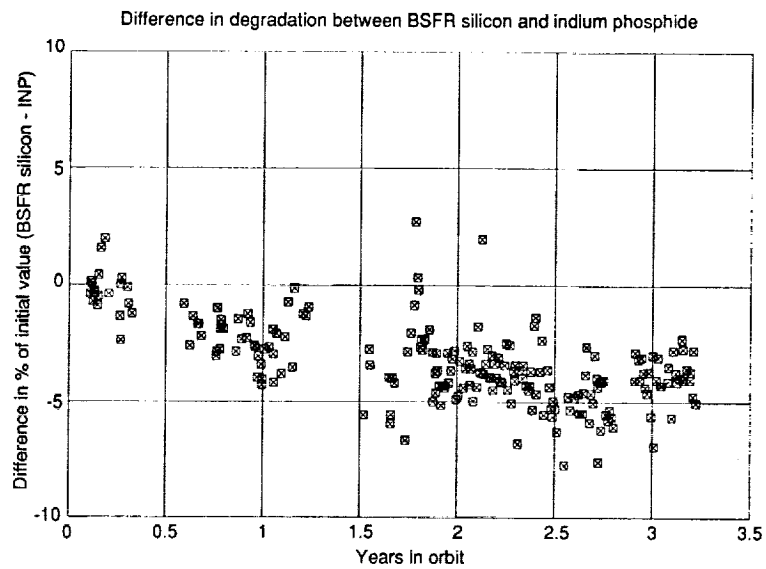


Fig 3 Lips III solar cell experiment

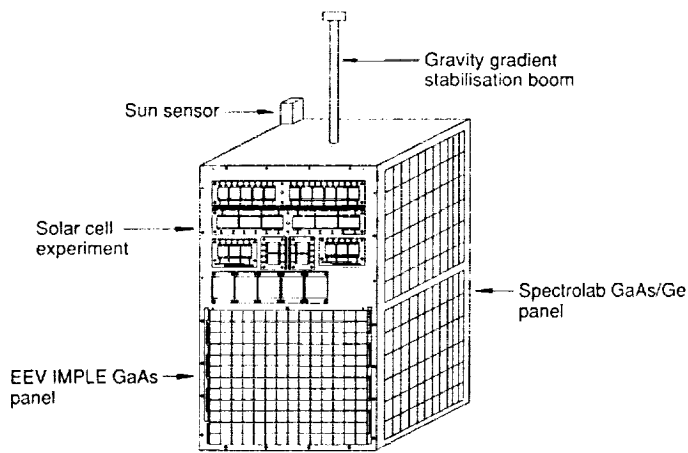


Fig 4 UoSAT - 5

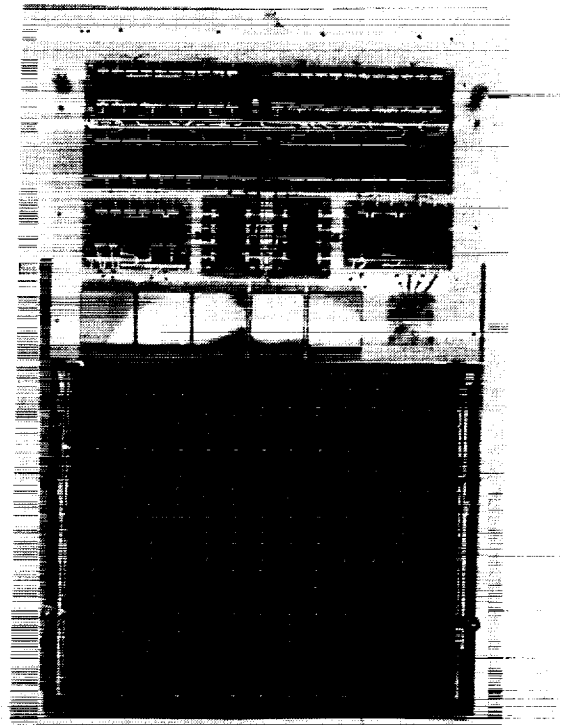


Fig 5 UoSAT-5 solar cell experiment - (Ref.33)

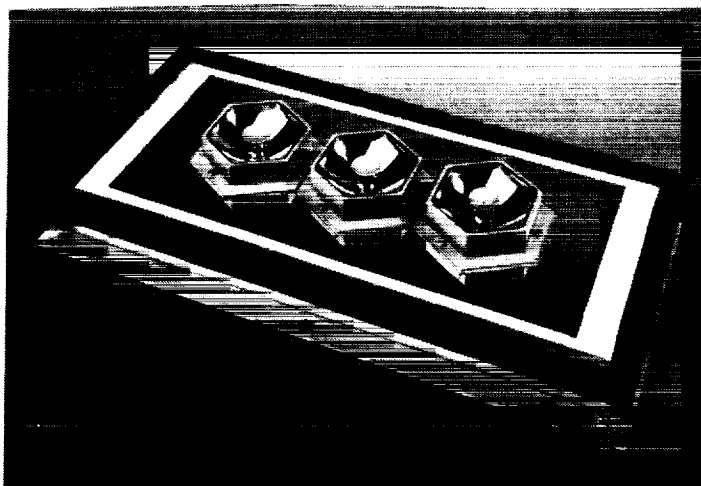


Fig 6 The Eureea concentrator experiment

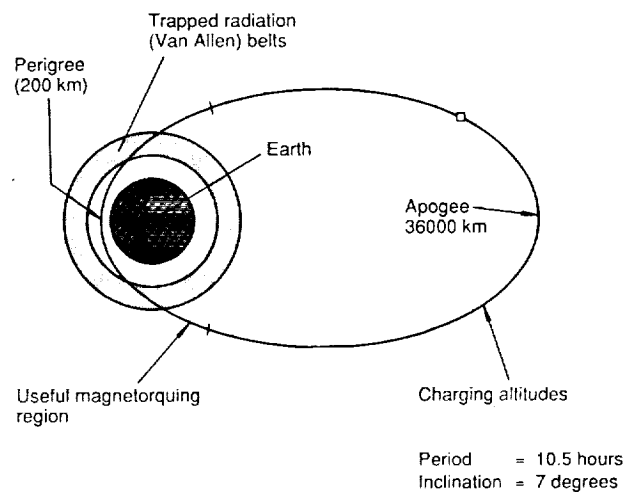


Fig 8 STRV - 1 geostationary transfer orbit

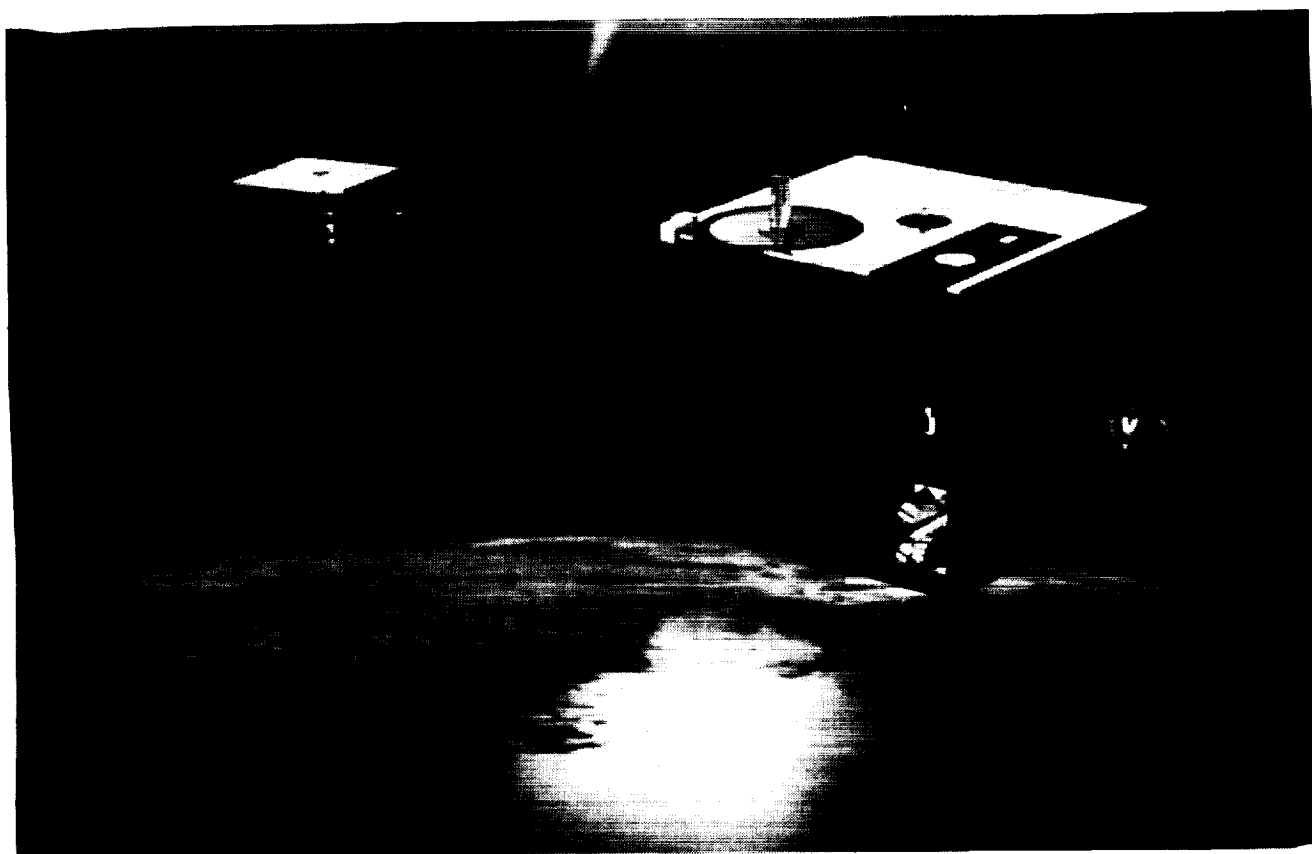


Fig 7 STRV - 1 satellites